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The Need for High Resolution Satellite Coverage including Thermal (surface temperature) for Water Resources Management

(i.e., Landsat resolution or similar)

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Western and southeastern water resources are dominated by diversions by irrigated agriculture. Management of these diversions requires quantification of water consumption (evapotranspiration) from irrigated crops that is possible only from satellite imagery. The resolution of the quantification must be fine enough to enable "seeing" water consumption by individual fields and land holdings.

If satellite coverage having the <u>high resolution</u> (30 m) of Landsat and the <u>continuous repeat cycle</u> of Landsat (each 16 days) is not continued, including the coincidentally collected images of <u>surface temperature</u>, then the current and extensive high resolution mapping programs by state and federal agencies that quantify water consumption from irrigated and other agricultural and natural systems will be substantially impaired.

Accurate and detailed information on water consumption has been a long-standing critical need in river and water resources management. Quantification of consumption is increasingly needed as water resources come under more and more tension by more and more users and interests and as water is transferred to cities and environment. The scientific community has long been researching the use of dependable satellite information to fulfill this quantification need, and now image processing programs designed to utilize the long record of Landsat imagery are finally in place for application to extensive areas of the United States. These processing programs locate and

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quantify the consumption of diverted water resources that occurs via the process of evapotranspiration (ET)[2].

Unfortunately, the longstanding Landsat satellite system that is critical to serving these critical water resources needs is in jeopardy of phase-out and abandonment by the US government. Only two Landsat's are in orbit and one, Landsat 5 (1984 launch), is nearly out of fuel and the other, Landsat 7 (1998 launch), was damaged in 2003 and its usability is greatly impaired.

In the **short to mid-term**, w**hat is critically needed** to service critical needs in water resources management is the following:

- An array of new Landsat or similar satellites (preferably four) as a separate system or in conjunction with other satellite platforms
- Each Landsat sensor system equipped with at least one **thermal band** sensor (for the calculation of surface temperature) at a minimum of 60 m resolution.
- The satellite array operated to provide images every 4 to 8 days over the entire United States.

In the **short term**, to fill in before new Landsat class satellites with thermal bands can be designed, funded and launched, what is critically needed is:

- A ground-station operated by the USGS EROS center or other federal center to download Landsat-like satellite images from the Chinese-Brazilian CBERS satellite system[3].
    - The CBERS system is comprised of two (soon to be three) satellites launched in 1999, 2003 and 2006 that have somewhat coarser resolution in the thermal band (80 to 160 m as compared to 60 m for Landsat 7's thermal band). However, this system could help fill in for Landsat while a new Landsat constellation (having a high resolution thermal band) is designed and launched. The CBERS satellites are only designed for mission lifespans of two years, however, so the CBERS system may not be a viable long-term solution. However, CBERS may be the only solution if a high resolution thermal band is not included on future Landsat data continuity missions.
    - Presently, CBERS data are only downloaded over Asia and Brazil. No ground-station exists in North America to download images for the United States.

[2] Evapotranspiration is synonymous with the term "consumptive use" and refers to the conversion of liquid water at or below the surface into the vapor form through the process of evaporation and transpiration (through vegetation). ET by irrigated agriculture is by far the largest consumer of western rivers and ground water.

[3] http://www.cresda.cn/ and http://www.cbers.inpe.br/en/programas/cbers1-2.htm

Background

The Landsat satellite system was inaugurated in 1972 and has provided routine high resolution imagery of the earth's surface ever since. Landsat number 4, launched in 1982, included a special thermal sensor for measuring temperature of the earth's surface at high spatial resolution. This sensor has enabled the calculation of evapotranspiration at the Earth's surface via complex surface energy balances. Landsat 4 was followed in 1984 with Landsat 5 and in 1998 with Landsat 7 (The Landsat 6 rocket crashed during launch). Landsat 5 and Landsat 7 are still functioning today, although Landsat 7 was partially damaged by unknown causes on May 31, 2003 and so far, its images have not been useful for routine ET calculation.

The nearly explosive **increase in the use** of image data from Landsat for computing evapotranspiration since year 2000 is an outgrowth of:

1) the significant lowering of costs for Landsat images (by a factor of 10) since 1998;
2) successful research in developing dependable processes for computing ET from satellite images,
3) advances in computer data storage and data handling abilities within water resources administrative units and the ability to process and integrate water consumption maps;
4) increased litigation and mitigation between environmental needs, endangered species concerns, and historical water use, and
5) pressure from state water resources entities such as Idaho Department of Water Resources (IDWR) for such an operational product.

As an example, in **Idaho**, the Idaho Department of Water Resources uses water consumption maps derived from Landsat satellites for:

1) water rights management and regulation;
2) hydrologic modeling;
3) prediction of incidental ground-water recharge from surface irrigation;
4) quantification of water consumption during water rights litigation;
5) management of stream diversions for endangered species; and
6) prediction of water consumption changes due to the transition of land use from agriculture to city.

Other uses of water consumption prediction by satellite include:

1) monitoring impacts of deficit irrigation of orchards and vineyards to conserve water in the Sacramento River system (**California**),
2) forecasting crop water demands for river management (Middle Rio Grande in **New Mexico**),
3) quantifying the areal extent and amount of water consumption by riparian vegetation (**New Mexico** and **California**),
4) quantifying transferable water during land fallowing (**California**),
5) quantifying state wide consumptive use as part of a state water plan (**California**)
6) helping farmers determine actual irrigation water needs during state mandated conservation programs (**Kansas**),
7) helping states comply with upper limits on water consumption under interstate compacts (**Wyoming**, **Nebraska**, **Utah**, **Idaho**), and
8) helping cities assess the impact of ground-water pumping on surface hydrology (**Florida**).

With the 2003 malfunction of Landsat 7, useful satellite images for ET computation are available only from Landsat 5 and only every 16 days. Clouds preclude the processing of images for ET, so that water consumption maps can now be guaranteed only about once every 2 months. This frequency is insufficient for following the seasonal changes of ET resulting from plant growth and water availability.

Specific Concerns

The specific concerns with the current Landsat satellite system and with the Landsat Data Continuity Mission (LDCM)[4] include the following:

a) Landsat 7 has malfunctioned and no longer provides complete image information for all of its coverage
b) Landsat 5 may have only one to two years of service life and fuel remaining before it fails
c) NASA plans for future Landsat satellites under the LCDM and the NPOESS[5] missions **do not contain the high resolution thermal band sensor** (i.e., for

[4] http://ldcm.nasa.gov/

[5] National Polar-orbiting Operational Environmental Satellite System (http://www.ipo.noaa.gov/). The NPOESS VIIRs sensors have only 400 m resolution, which is too coarse for irrigated agriculture and water resources management (http://www.ipo.noaa.gov/Technology/viirs_summary.html). The NPOESS may be expanded to contain Landsat-scale (resolution) sensors (Memo from John Marburger, Director of Office of Science and Technology Policy, Aug. 13, 2004). **However, the all-important thermal band is not planned for inclusion.** Therefore, the expanded NPOESS - LCDM combination would not be

computing surface temperatures). The high resolution **thermal band sensor is critical** for applying the SEBAL and METRIC evapotranspiration mapping procedures at sufficient resolution to quantify water consumption by individual farms (fields) and water rights holdings.

d) **NASA cancelled the solicitation** for the Landsat Data Continuity Mission (LDCM) implementation phase as of September 26, 2003 that was to launch Landsat 8, albeit **without any thermal band sensor** that is critical to consumptive water use mapping.

e) **NASA has been reluctant to consider and understand the importance of the Landsat mission (including its thermal mapping) in water resources management**.

f) **No ground-link** for the Sino-Brazilian Landsat-like satellite system exists for the United States, nor some kind of a mutual-use agreement that would enable the use of the CBERS program for the short-term. In addition, the quality and reliability of the CBERS images are in question and must be investigated.

Current Image Processing

Two of the primary processing programs used to predict high resolution ET from satellite images are the **SEBAL** procedure (Surface Energy Balance Algorithms for Land) of SEBAL North America, Inc.[6] and the **METRIC** procedure (Mapping EvapoTranspiration at High Resolution with Internalized Calibration) of the University of Idaho[7]. These relatively sophisticated, energy-balance based programs produce **maps of ET** having **30 m by 30 m** (100 ft by 100 ft) resolution when used with **Landsat** images. This high resolution allows water resources managers and administrators to identify the water consumed from individual fields and within individual water rights. The combined use of images from both Landsat 5 and Landsat 7 satellites prior to the May, 2003 malfunction of Landsat 7 provided high resolution images that were updated potentially every 8 days.

Table 1 summarizes recent applications of SEBAL and METRIC processing. Water resources are becoming critically strained and the future management and planning analyses need the accurate and detailed information on water consumption afforded by satellite data. The use of such information is spreading across the United States. **State and federal water resources agencies are discovering the immense value of evapotranspiration information produced by the SEBAL and METRIC processes and are incorporating this information into routine operations**, as evidenced by a recent national conference on Evapotranspiration by Remote Sensing sponsored by the U.S. Bureau of Reclamation[8].

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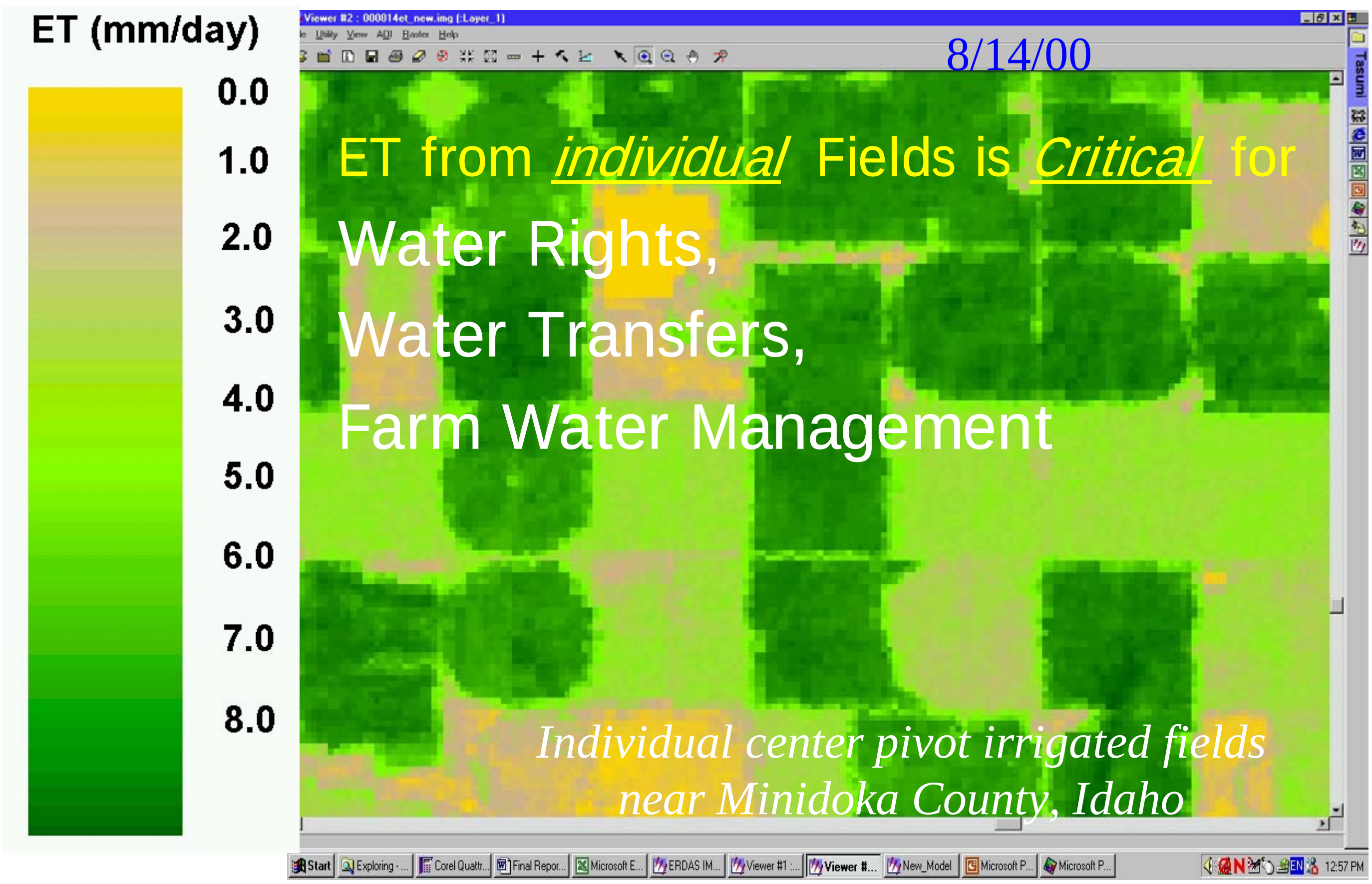
useable for quantifying water consumption from individual irrigated and agricultural fields necessary for future management levels.

[6] www.sebal.us

[7] http://www.kimberly.uidaho.edu/water/metric/index.html

[8] Feb 8-10, 2005, Ft. Collins, Colorado.

SEBAL and METRIC are currently preferred over other satellite-based ET process models in the western United States because of the use of internalized calibration procedures[9]. These procedures index sensible heat fluxes from land surfaces (one of the major energy balance components) to satellite measured surface temperatures at specific surface boundary conditions. The indexing of the heat flux to available ground weather data eliminates the need for atmospheric correction of short-wave and thermal information in images[10].



[9] Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, and A.A.M. Holtslag, 1998. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology* 212-213:198-212.
Allen, R.G., A. Morse, and M.Tasumi. 2003. Application of SEBAL for Western US Water Rights Regulation and Planning. Proc. Int. Workshop on Use of Remote Sensing of Crop Evapotranspiration for Large Regions. 54th IEC Meeting of the International Commission on Irrigation and Drainage (ICID), Montpellier, France, Wednesday, 17 September, 2003. 13 pages. On web at: http://www.kimberly.uidaho.edu/water/montpellier/p10/Allen_P.pdf
with presentation at http://www.kimberly.uidaho.edu/water/montpellier/p10/index.html

[10] Tasumi, M. 2003. Progress in operational estimation of regional evapotranspiration using satellite imagery. Ph.D. Dissertation, University of Idaho, Moscow, Idaho.
Trezza, R. 2002. Evapotranspiration using a satellite-based surface energy balance with standardized ground control. Ph.D. Dissertation, Utah State University, Logan, Utah.

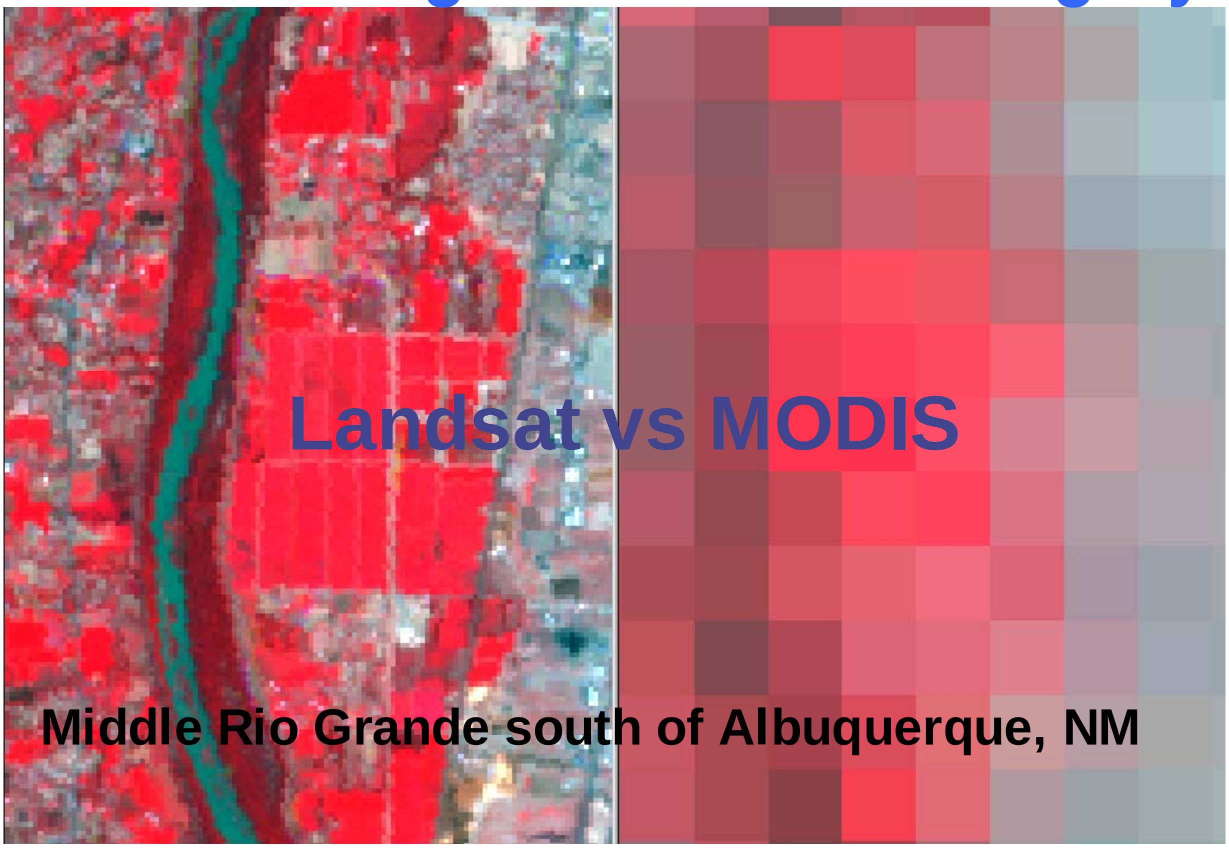
Table 1. Applications of **SEBAL** or **METRIC** in the United States that have relied on **Landsat** satellite imagery (including the **thermal band**) to produce maps of water consumption (evapotranspiration).

State(s)	**River Basin**	**Year(s) of Study**	**Year(s) of Images**	**No. Studies**	**Applier**	**Client**	**Use of Water Consumption maps**
Idaho, Utah, Wyoming	Bear River	2000	1985	1	Univ. Idaho, Idaho Dept. Water Resources http://www.kimberly.uidaho.edu/water/metric/1_02ERDAS.pdf	Idaho Dept. Water Resources	Bear River Compact Compliance
New Mexico	Middle Rio Grande	2000, 2003	2000, 2002	4	WaterWatch, New Mexico Tech, SEBAL North America, Univ. Idaho	New Mexico Tech, USBR, Keller-Bliesner Engineering, U.S. Dept. Justice	Endangered Species Issues, Impacts of water table on water consumption
Florida	Tampa Bay	2000	2000	1	Allen Engineering, Waterstone, Inc.	Tampa Bay Water	Impacts of ground-water pumping on ET of natural vegetation
Idaho, Montana, Utah, Nevada	Snake River	2001, 2002, 2003	1986, 1988, 1989, 1990, 1991, 2000, 2002	3	University of Idaho http://www.kimberly.uidaho.edu/water/montpellier/p10/Allen_P.pdf	Idaho Dept. Water Resources	Prediction of ground-water recharge and spring flow, Regulation of ground-water permits
Idaho, Oregon	Boise River	2002	1997, 2001	1	Idaho Dept. Water Resources	USBR, Idaho Dept. Water Resources	Transition of agriculture to residential, planning reservoir operations
Texas	East Texas	2002	2000	1	Interra	State of Texas	Multi-basin water balance
New Mexico	San Juan	2002	2002	1	WaterWatch, Keller-Bliesner Engineering	Navajo Agricultural Products Industry (NAPI)	Management of center pivot irrigation
California	Lower Colorado River	2003	2002, 2003	1	Univ. Idaho	Metropolitan Water District	Spatial and seasonal trends in agricultural water use

Table 1 Continued. Applications of **SEBAL** or **METRIC** in the United States that have relied on **Landsat** imagery (including the thermal band) to produce maps of water consumption.

State(s)	**River Basin**	**Year(s) of Study**	**Year(s) of Images**	**No. Studies**	**Applier**	**Client**	**Use of Water Consumption maps**
Idaho	Lemhi River Basin	2002	2000	1	IDWR, Univ. of Idaho	IDWR	Water balance for hydrologic modeling and water rights management
Idaho	Salmon River Basin	2003	2003	1	IDWR, Univ. of Idaho	IDWR	Improving streamflow for fish listed under the Endangered Species Act
Washington	Yakima River	2003	2001	1	SEBAL North America	Benton Irrigation District/USBOR	Quantification of ET for negotiation of diversion reduction agreement
California	Russian River				SEBAL North America	Sonoma County Water Agency	Hydrologic modeling leading to assessment of compliance with water rights
California	State-wide	2004	2002	1	SEBAL North America (see www.sebal.us) (using MODIS satellite with validation via Landsat)	Proof of Concept	State-wide ET by month for use in the State water plan, etc.

Need for High Resolution Imagery



Landsat False Color (MRG)
8/26/2002 10:33am

MODIS False Color (MRG)
8/26/2002 11:02am

The Specific Need for Landsat and its high resolution Thermal band

Other satellites besides **Landsat** can be used to create maps of evapotranspiration, but not with the same <u>high (30 to 60 m) resolution</u>:

- Although the **MODIS** satellite (1999 first launch) has a daily return time (one overpass per day) and is adequate for ET mapping, **its resolution is only 1000 m** (0.6 mile) actual and 2000 m useable, <u>which makes the identification of water consumption from individual fields</u> (generally having dimensions of 200 to 800 m) and for individual crops <u>impossible</u> (see figure above).
- The **ASTER** satellite sensor (1999 launch) has an 8 day return time, which is adequate for ET mapping, but **communication downlink constraints** prohibit continuous collection of image data. Thus, continuous coverage of large areas of the United States or even irrigated areas of the west is not possible.

- The **AVHRR** satellite of NOAA has similar resolution as MODIS and similar constraints. Although AVHRR and MODIS can be used to provide ET maps for large areas that are useful for hydrologic and global climate change studies, the **resolution is not sufficient** to provide the evapotranspiration information required for the wise management of our seriously stretched water resources (especially in the irrigated areas of the west).
- The **GOES** satellite system provides continuous, near real-time coverage of all points of the United States. However, this satellite **lacks the spatial resolution** necessary for the accurate and detailed computation of water consumption by agriculture.
- The future "next generation" **NPOESS** (National Polar-orbiting Operational Environmental Satellite System) (earliest launch in 2009), while having superior spectral and thermal sensors and information, <u>will suffer the same deficiencies of MODIS and AVHRR</u> for energy balance and evapotranspiration determination, in that the image resolution will only be about 700 m in the bands required for ET modeling. NPOESS may be expanded to contain Landsat-scale (resolution) sensors (Memo from John Marburger, Director of Office of Science and Technology Policy, Aug. 13, 2004). However, <u>**the all-important thermal band is not planned for inclusion at the current Landsat resolution**</u>. Therefore, the expanded NPOESS - LCDM combination will not be useable for quantifying water consumption by individual stakeholders in irrigated agriculture.
- Other high resolution satellites such as the French **SPOT** and Indian **ISIS** satellites **do not measure surface temperature** and are therefore **unusable** with the energy-balance based SEBAL and METRIC processes for ET mapping
- No downlink is available for Landsat-like images acquired by the Sino-Brazilian CBERS satellites when over North America.

In NASA's own words: "*No other current or planned remote sensing system, public or private, fills the role of Landsat in global change research or in civil and commercial applications*."[11]

It was the intention of NASA and Congress since 1992[12] to continue support for this critical Earth-imaging program that includes monitoring of land surface temperature (critical to the calculation of evapotranspiration). The noted NASA publication on Landsat goes on to state: "<u>***Landsat 7 will fulfill its mission***</u> *by providing repetitive, synoptic coverage of continental surfaces; spectral bands in the visible, near-infrared, short-wave, and* <u>***thermal infrared***</u> *regions of the electromagnetic spectrum; spatial resolution of 30 meters (98-feet); and absolute radiometric calibration.* <u>***No other current or planned remote sensing system matches this combination of capabilities***</u>." Unfortuntately, Landsat 7 is damaged and no follow-on is planned with the same high resolution <u>**thermal**</u> sensor.

[11] http://pao.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/earthsci/landsat/landsat7.htm
[12] The 1992 Land Remote Sensing Policy Act

Continued Landsat imagery is imperative to western and southeastern water resources management for the following reasons:

1. **High resolution**. The 30 m short-wave resolution and 60 m thermal resolution of Landsat satellites is critical for the computation and mapping of evapotranspiration from individual irrigated fields. Water rights regulation and administration are critically tied to identification and quantification of water consumption on a **field by field basis**. The current ET mapping by the Idaho Department of Water Resources (IDWR) could not have been developed if the high-resolution Landsat images had not been available. The high-resolution Landsat images also provide a means for identifying the crop type for each field that is useful for characterizing trends in evapotranspiration and for establishing relationships between water consumption and crop type (for example work by the U.S. Bureau of Reclamation in California and Arizona). The detailed and accurate computation of evapotranspiration using Landsat satellite data is not possible with the 1 km resolution of MODIS and AVHRR satellites.
2. **Continuous coverage**. Landsat satellite images are available for every portion of the United States for nearly every overpass date. This **continuous coverage is critical for tracking the change of water consumption** over time and space for individual fields, irrigation projects, river basins, and regions. Continuous surface coverage is not possible with the ASTER satellite. ASTER coverage must be ordered ahead of time and there is substantial competition within the scientific community for this information. In water resources management and conflict resolution and in issues involving endangered species, we often must look back in time to quantify historical water consumption and historical trends. Rarely do we have the foresight to “order on” a satellite platform such as ASTER ahead of the needed date. Recent Idaho applications of SEBAL and METRIC have processed Landsat images as far back as 1985[13].
3. **Long image history**. Landsat images (including thermal information) have been available for much of the United States since the early 1980’s. This historical data has been extremely valuable for water resources management because it provides information on changes in water consumption over time for specific areas. **Long, continuous records are essential for hydrologic studies** and ecological and endangered species studies on the impacts of land use change. The implementation of the Landsat Data Continuity Mission is crucial to the future of water consumption mapping having adequate resolution, return cycle, and coverage.
4. **Workable return time**. The 16 day return time of Landsat (8 days with both Landsat 5 and 7 satellite) has been sufficient to establish trends in water consumption caused by growth and death of vegetation and change in weather.

[13] Morse, A., M. Tasumi, R.G. Allen and W.J. Kramber, 2000. Application of the SEBAL Methodology for Estimating Consumptive Use of Water and Streamflow Depletion in the Bear River Basin of Idaho through Remote Sensing: Final Report. Idaho Department of Water Resources, Idaho

Shorter return times (i.e., with multiple Landsats) would be even better. However, two Landsat satellites are sufficient to provide three cloud-free high resolution images per month during summer in most western regions. Four Landsat satellites would provide even better temporal data for the western states and would provide some backup capacity in the event of satellite failure.

We see a tremendous future for the use of Landsat thermal band information in water resources management in the United States, that would justify the cost of a complete, fortified, stand-alone Landsat program. Morse[14] has conservatively estimated cost savings of ground-water pumping monitoring over a ten year period for the western United States through the use of Landsat-based water consumption maps as opposed to expensive and problematic pump flow measurements, site visits, and checking of power consumption records. He has estimated the ten-year value at about 1 billion dollars, which far exceeds the total cost for the Landsat 8 program. The potential savings for this one application, alone, are enormous. Mapping of consumptive use is also critical for surface water management.

The Landsat satellite replacements or other satellite systems **<u>must</u> measure surface temperature** (i.e., have at least one thermal band sensor) coincident with the short-wave images for the computation of water consumption maps.

Reasons given by NASA[15] for not including a thermal band sensor in future Landsat missions are:

1 The cryogenically-cooled, older technology used on present Landsat satellites is too expensive and heavy to put on the future Landsat Data Continuity Mission (LDCM).

2 New microbolometer technology for measuring earth surface temperature is still relatively immature and perhaps too risky to incorporate on the LDCM.

3 NASA has not been able to identify a sufficient customer base for thermal (surface temperature) data.

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[14] Morse, A. 2003. Comparison of Ground Water Monitoring Costs as a Reason to Maintain the Thermal Band on the Landsat Data Continuity Mission: A Quick Look. Internal Report to the Idaho Department of Water Resources, Boise, Idaho. Feb. 18, 2003, 5 p.

[15] Dr. Ghassem Asrar, NASA Associate Administrator for Earth Science in a letter dated August 7, 2003 to Drs. Paul Pinter and Bruce A. Kimball, USDA-ARS, Phoenix, AZ

Summary and Conclusions

The current ET mapping in Idaho, Utah, Wyoming, Montana, Washington, New Mexico, Texas and Nevada and California requires the high resolution of Landsat satellites (as opposed to MODIS or AVHRR) to identify ET from individual fields for purposes of water rights and irrigation water management, and requires the consistent return time and coverage of the Landsat system (as opposed to ASTER, which is intermittant at best).

1 With the damage to Landsat 7, we are now down to one single high-resolution, continuous coverage, thermal-sensor equipped satellite (Landsat 5) and it is nearing the end of its life;

2 High-resolution, continuous coverage thermal information is essential for the mapping of water consumption (evapotranspiration) in the U.S. Mapping of water consumption is imperative for
   a) quantifying actual depletions to the water resource caused by evapotranspiration of diverted water
   b) monitoring ground-water pumpage by individual landholders;
   c) mediating and mitigating water rights conflicts and impacts of water transfers; and
   d) solving endangered species issues related to water resources;

3 Several states besides **Idaho** are beginning or considering a substantial application of SEBAL, METRIC or related procedures including **New Mexico**, **Texas, California, Wyoming, Colorado, Florida, and Nebraska**.

4 The western U.S. is in the midst of an extended drought and better management of the water resource through more effective and economically efficient water use is essential.

5 A **short term solution** could be the establishment of a ground-station for downloading image data from the **Sino-Brazilian CBERS satellite system** that has spatial resolution and thermal band similar to Landsat.

Being down to a single Landsat satellite is like going into heart surgery with a failing electrical system and no backup power.

We need a working Landsat system that (ideally) is:

- An array of four Landsat satellites
- Each satellite is equipped with at least one thermal band sensor (for measurement of surface temperature) at a minimum of 60 m resolution.
- The array is operated to provide images every four days for all points within the United States.

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